

Investigating the Effect of Porosity on Thermal Characteristics of a 3D Orthogonal C-SiC Composite Using Finite Element Method

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Abstract

In this paper, finite element heat transfer analysis of a 3D orthogonal woven C-SiC composite is presented. Thermal transport properties of the composite are predicted in the three orthogonal directions. The effect of different manufacturing porosity types on thermal transport characteristics of the composite is also determined, which is achieved by using four unit cells constructed at different length scales. The predictive capability of the finite element models is benchmarked against the experimental results obtained from laser flash technique.

Keywords

CMC; 3D C-SiC Composite; Finite Element Modelling; Thermal Characteristics; Porosity

Introduction

High performance materials with a capability of reliable operation over long periods under high tensile stresses at elevated temperatures (up to 1500°C) and in oxidizing environments (Evans 1995), such as in nuclear and aerospace industries, are being continuously developed. Using these materials in aerospace engines and power generation plants, for example, results in less fuel consumption as well as less emissions (Farooqi and Sheikh 2006). This is due to increase in the energy efficiency which results from high operating temperature as well as reduced weight. The demand for these materials can be met by using ceramic matrix composites (CMC) due to their superior thermal properties and very low density (Chawla 2003). However, due to the anisotropic nature of fibres, thermal and mechanical properties through-thickness are much lower in 2D CMCs than that in-plane. Unlike 2D CMCs, the 3D orthogonal CMCs have equal distribution of fibres in all directions, which results in uniform properties in-plane and

through-thickness.

It is well established that the presence of manufacturing porosity in CMCs has a direct effect on their thermal transport properties. As a result, it is essential to predict the thermal properties of CMCs at an early stage in the design process (Puglia, Sheikh et al. 2005). Unfortunately, due to lack of homogeneity in woven fibre reinforced composites, it is not always possible to calculate the equivalent thermal and mechanical properties of such materials by using a specific set of equations such as the rule of mixture. For such materials with complex architectures, finite element method has been employed with a high degree of reliability and accuracy. This has led to a reduction in the amount of experimental work and hence the design and development costs. In recent years, a considerable amount of work has been done on predicting mechanical and thermal behaviour of 2D and 3D composites. Many researchers, such as Farooqi and Sheikh (Farooqi and Sheikh 2006), Tang et al (Tang, Blacklock et al. 2010), Zhang et al (Zhang and Hayhurst 2011), Li et al (Li, Li et al. 2011) and Youngblood et al (Youngblood, Senor et al. 2002), have developed models to predict thermal transport properties in 2D CMCs. However, fewer studies have been carried out on 3D composites. Schuster et al (Schuster, Heider et al. 2008) have predicted through thickness thermal transport properties for 3D orthogonal composites with different fibre matrix combinations. But the main limitation of their work is that the presence of the fibre-matrix interface and porosity is neglected.

In this work, a number of finite element models have been developed to determine the thermal transport properties of a 3D orthogonal woven C-SiC composite. The presence of different types of porosities is taken

into account by constructing appropriate unit cell models at different length scales. The FE predictions are validated by experimental results obtained using the laser flash technique (Kumar, Kumar et al. 2011).

Material under Investigation

The composite used in this study has been developed by DRDO (Defence Research and Development Organization, India) for aerospace applications. The architecture of this material consists of T300 (3K) carbon fibre tows which were used to form a 3D orthogonal fibre preform by weaving them in mutually perpendicular directions (x, y and z), as shown in Fig. 1.

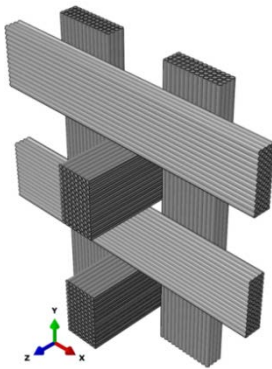


FIG. 1 3D ORTHOGONAL ARCHITECTURE

Constant spacing of 1.5 mm was maintained between two adjacent fibre tows in each direction. The material was produced by using a liquid silicon infiltration (LSI) process. In this process, the preform was infiltrated with a polymer which got thermally decomposed to leave carbon char. It was then infiltrated with liquid silicon which reacted with carbon char to produce silicon carbide (SiC) matrix around the carbon fibre tows. The final product was comprised of carbon fibres embedded in a carbon matrix and this as a whole was surrounded by SiC matrix. The volume fractions of carbon matrix, carbon fibre and SiC were calculated by DRDO using acid digestion method and they were found to be 25%, 19% 56% respectively. In addition, it is important to emphasise that two different volume fractions are involved in the calculations. The first one is 43.2% carbon fibre within the carbon matrix to form the fibre tow. The second one is 44% fibre tow in the composite with remaining surrounded by SiC matrix. The properties of fibre tow and SiC matrix were calculated by using the rule of mixtures (equations 1, 2 and 3). Table 1 shows the material properties for each material.

$$\rho_{\text{composite}} = \rho_{\text{fibre}} V_{\text{fibre}} + (1 - V_{\text{fibre}}) \rho_{\text{matrix}} \quad (1)$$

$$C_{\text{composite}} = C_{\text{fibre}} V_{\text{fibre}} + (1 - V_{\text{fibre}}) C_{\text{matrix}} \quad (2)$$

$$k_{\text{composite}} = k_{\text{fibre}} V_{\text{fibre}} + (1 - V_{\text{fibre}}) k_{\text{matrix}} \quad (3)$$

Where ρ , C , k and V are density, specific heat, thermal conductivity and volume fraction respectively.

Manufacturing Porosity

Cracks and voids have a direct effect on thermal and mechanical properties of ceramic matrix composites. Hence, their effects should be included in the property (thermal diffusivity, for example) prediction of the composite. In an earlier work done by Paolo Del Puglia et al. (Puglia, Sheikh et al. 2003), the manufacturing porosity within a 2D plain wave C-SiC composite (DLR-XT) was classified and quantified. Fig. 2 shows the different types of porosity in DLR-XT, which were observed and measured using optical and scanning electron microscopy (SEM).

TABLE 1 MATERIAL PROPERTIES FOR THE CONSTITUENT MATERIALS

Material Property	Carbon Fibre	Carbon Matrix	SiC Matrix	Composite
Density (Kg/m³)	1760	1373	2850.2	2273.8
	1540.2 (Fibre Tow)			
Specific Heat (J/Kg-K)	750	717.5	776.5	765.7
	731.5 (Fibre Tow)			
Thermal Conductivity (W/m-K)	83 (//)	30	120.7	81.34
	8.3(⊥)			

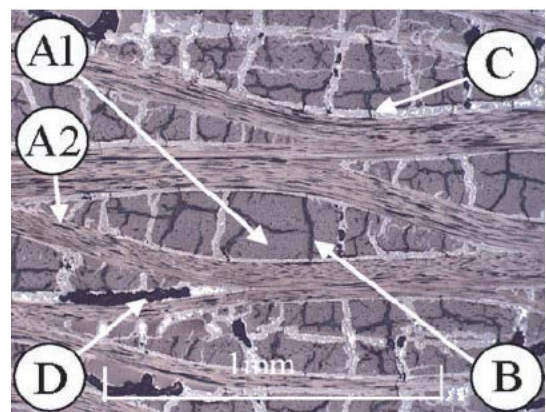


FIG. 2 DIFFERENT TYPES OF MANUFACTURING POROSITY IN CMC (PUGLIA, SHEIKH ET AL. 2003)

Inter-fibre Micro-crack Porosity (Class A)

Inter-fibre micro-porosity can take two forms, either spherical pores (A1), or large cracks (shrinkage debonding) (A2). These two kinds of porosity may be

observed between neighbouring fibres with in a tow. Spherical pores result from incomplete infiltration whereas shrinkage debonding is generated during cooling as a result of thermal contraction and mismatch of thermo-mechanical properties between fibres and matrix.

Trans-tow Cracks (Class B)

These types of cracks occur between the adjacent fibres within the same tow. It penetrates the tow in a direction parallel to the fibres.

Matrix Cracks (Class C)

The matrix cracks run through the matrix in a direction perpendicular to the fibre tow. This type of cracks provides a pathway for oxygen that further leads to the oxidation of carbon fibre and interface (Xu and Zhang 2011).

Denuded Matrix Region (Class D)

This class of porosity is composed of large voids which occur at the intersection of four tows for a plain weave. These voids are also generated during the manufacturing process due to incomplete infiltration.

The quantification and classification of different types of porosity has not been carried out for the 3D woven composite used in this study. However, as the material is produced by the same LSI technique under similar processing conditions and with the same constituent materials as DLR-XT used by Paolo Del Puglia (Puglia, Sheikh et al. 2003), it is considered appropriate to use the same porosity classification and quantification data for the current analysis. However, class D porosity is less likely to be produced in the 3D orthogonal fabric due to fibres architecture in this material which does not intersect with each other. Table 2 and 3 summarise the measurements of class A, B and C.

TABLE 2 POROSITY LEVELS OBTAINED FROM THE EXPERIMENTAL EVIDENCE FOR POROSITIES OF CLASSES A

Class	Types	Area fraction
A1	Area fraction of the spheres	0.02
A2	Area fraction of the shrinkage debonding	0.0059
A2	Length of major-axis of debonding surface = 0.06 mm	–
A	Total area fraction for porosity of Class A	0.0259

Courtesy: Del Puglia et al.(Puglia, Sheikh et al. 2003)

TABLE 3 CRACK GEOMETRY AND PERIODICITY FOR CLASSES B AND C POROSITY

Class	Cracks main characteristics
B	Crack depth = $1.28 \times$ tow diameter
B	Equivalent number of cracks in planes parallel to tow axes = 2
B	Crack length = $1.1 \times$ tow diameter
C	Crack separation or periodicity = $0.308 \times$ tow diameter
C	Crack length = tow circumference
C	Crack depth = SiC matrix thickness = 0.0225 mm
	Average tow diameter = 0.18 mm

Courtesy: Del Puglia et al.(Puglia, Sheikh et al. 2003)

Experimental Setup

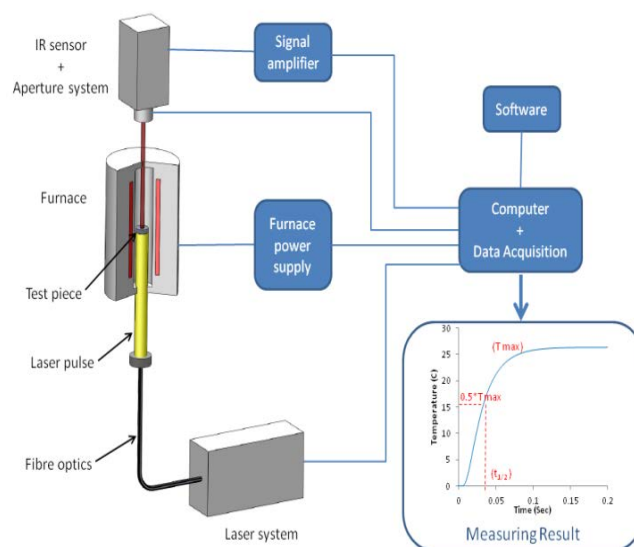


FIG. 3 THE PRINCIPLE OF THE LASER FLASH TECHNIQUE

The experimental work produced earlier by Kumar et al.(Kumar, Kumar et al. 2011) has been used in this study for validation purposes in which the thermal diffusivity α was measured in the three orthogonal directions (x , y and z). They used laser flash technique which was first proposed by Parker et al. (Parker, Jenkins et al. 1961) in 1960. This method depends on the application of a laser pulse to the entire front face of the specimen for few milliseconds to record the temperature changes as a function of time on the back face of the specimen. From the recorded data, the time to reach half of the maximum temperature, which is called the half rise time ($t_{1/2}$), has been obtained. For a thin disc specimen with one face uniformly irradiated (1-D heat flow), thermal diffusivity was then calculated by using equation (4). Fig. 3 shows the

principle of the laser flash technique.

$$\alpha = 0.1388L^2/t_{1/2} \quad (4)$$

Where α is thermal diffusivity, L is the sample (disc) thickness and $t_{1/2}$ is half rise time.

Finite Element Modelling

Modelling the Unit Cell

Modelling of composite materials can be simplified by modelling a representative unit cell which should produce the microstructure of the composite by repeating itself through translation in the three spatial planes (Farooqi and Sheikh 2006). Many researchers such as Ismar et al. (Ismar and Schröter 2000), Woo and Goo (Woo and Goo 2004), Carvelli and Poggi (Carvelli and Poggi 2001) and Zako et al. (Zako, Uetsuji et al. 2003) have adopted this approach. The Finite Element unit cell used for the present material is a cube containing SiC matrix and carbon fibre tows, with rectangular cross section, equally distributed in all directions as shown in Fig. 4. Sharma et al. (Sharma, Mahajan et al. 2010) and Roa et al. (Rao, Mahajan et al. 2008) have adopted similar unit cells in their mechanical analyses. Fig. 5 shows finite element mesh of the unit cell composed of 148119 linear tetrahedral elements of type DC3D4 in ABAQUS. The thermal diffusivity of the composite unit cell was measured by a 1-D heat flow transient thermal analysis which simulated the laser pulse heating technique.

Steady-State and Transient Thermal Analysis

There are two types of finite element thermal analyses: steady state and transient. The thermal conductivity is measured by steady state thermal analysis which involves the application of a temperature gradient across the unit cell where the rest of the faces are thermally insulated, as shown in Fig. 6a. The thermal conductivity in the direction of applied temperature gradient (say x) is calculated by using Fourier's law as:

$$k_x = q_x \frac{\Delta x}{\Delta T} \quad (5)$$

Where k_x is the thermal conductivity of the composite and q_x is total heat flux in x -direction.

q_x is calculated from the simulation of the nodal flux values across the face with the lower temperature as follows:

$$q_x = \sum_{i=1}^N q_i A_i / \sum_{i=1}^N A_i \quad (6)$$

Where N is the number of element surfaces, q_i and A_i are the average of the nodal flux values and the surface area of the i th element.

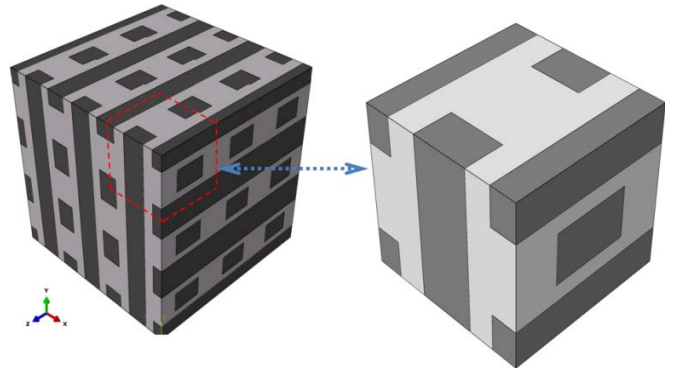


FIG. 4 THE COMPOSITE UNIT CELL

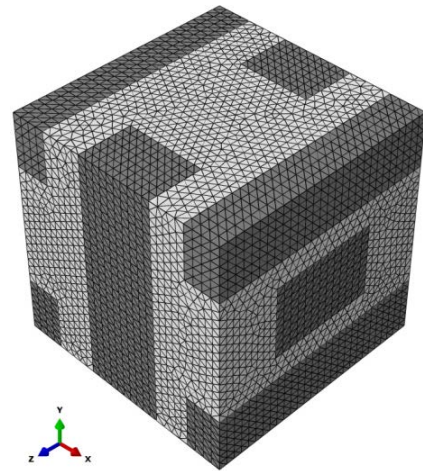


FIG. 5 FINITE ELEMENT MESH OF THE COMPOSITE UNIT CELL

The thermal diffusivity on the other hand is measured by a transient thermal analysis which simulates the laser pulse heating technique as described before in the experimental setup. The transient analysis involves the application of heat flux to one face of the unit cell for a few milliseconds and records the temperature changes as a function of time on the back surface, while the surrounding faces are thermally insulated, as shown in Fig. 6b. From the temperature history, the time to reach the temperature equal to half of the maximum average temperature, the half rise time ($t_{1/2}$), is obtained. The thermal diffusivity is then calculated by using equation (4). T_{av} on the back surface of the unit cell can be calculated by the following equation:

$$T_{av} = \sum_{i=1}^N T_i A_i / \sum_{i=1}^N A_i \quad (7)$$

Where N is the number of element surfaces, T_i and A_i are the average nodal temperature value and surface area of the i th element respectively.

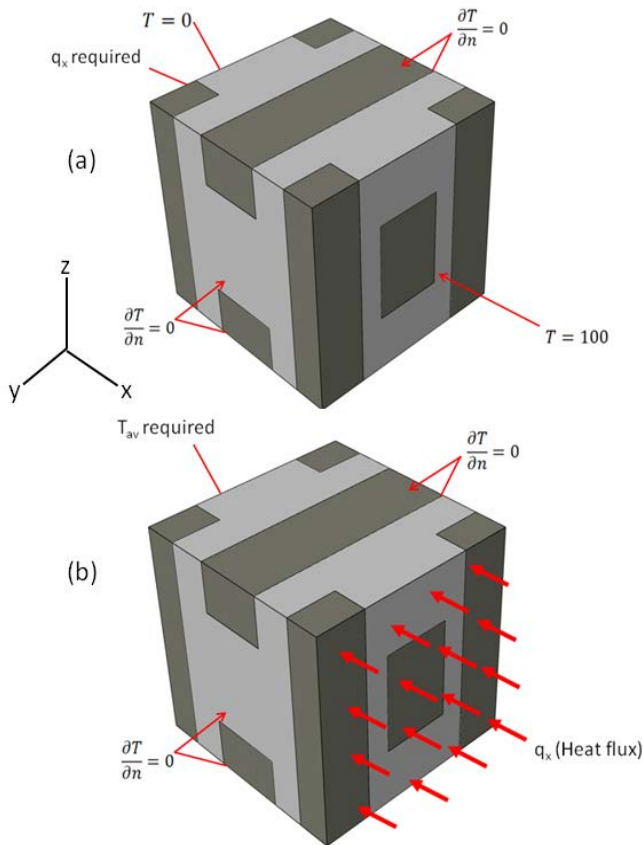


FIG. 6 BOUNDARY CONDITIONS FOR (A) STEADY STATE (B) TRANSIENT FE THERMAL ANALYSIS IN X DIRECTION

Modelling Different Types of Porosity

To include the effect of the different types of porosity on thermal transport properties, three micro unit cells one for each type of porosity (class A, B and C) were constructed and used in a sequence as shown in Fig. 7. The thermal conductivity values obtained from a finite element thermal analysis of model A are incorporated in model B. Similarly, the thermal conductivities from model B are used in model C. The composite unit cell then incorporates the combined effect of the three types of porosity, which results from model C. Also, to evaluate the effect of each type of porosity, the thermal conductivities resulted from model A and B are used in the composite unit cell.

1) Class A Porosity (Model A)

A carbon fibre tow is modelled with 16 carbon fibres surrounded by carbon matrix. The spherical pores (A1 porosity) and shrinkage debonding (A2 porosity) are included in this model as shown in Fig. 8. Model A comprises of 43.2% carbon fibre, 2% and 0.6% class A1 and A2 porosity respectively (from Table 2), while the rest is carbon matrix. Materials properties assigned for each phase were taken from Table 1. The longitudinal and

transverse thermal conductivities of the carbon tow have been calculated with and without the presence of class A porosity. The results are given in the second and third columns of Table 4.

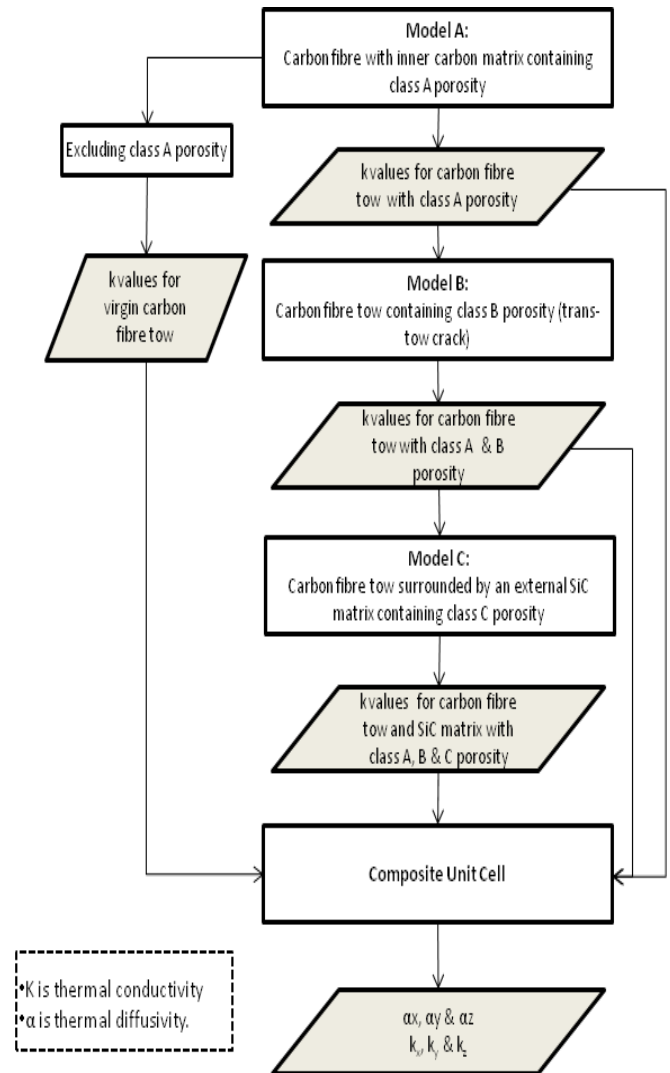


FIG. 7 FLOW CHART SHOWING THE MODELLING STRATEGY

2) Class B Porosity (Model B)

The output results from model A have been used in model B which is a micro unit cell of a carbon fibre tow containing a trans-tow crack (class B) of depth 'd' as shown in Fig. 9. The carbon fibre tow was modelled as a single phase but with orthotropic properties. Both longitudinal and transverse thermal conductivities were obtained from the steady state analysis. The results are given in the fourth column of Table 4.

3) Class C Porosity (Model C)

The matrix crack was modelled as a circumferential crack around the carbon tow, as shown in Fig. 10. The model was constructed to take into account the

matrix cracks with an average periodicity 'P'. The longitudinal thermal conductivity was obtained from the steady state analysis. The result is given in the last column of Table 4.

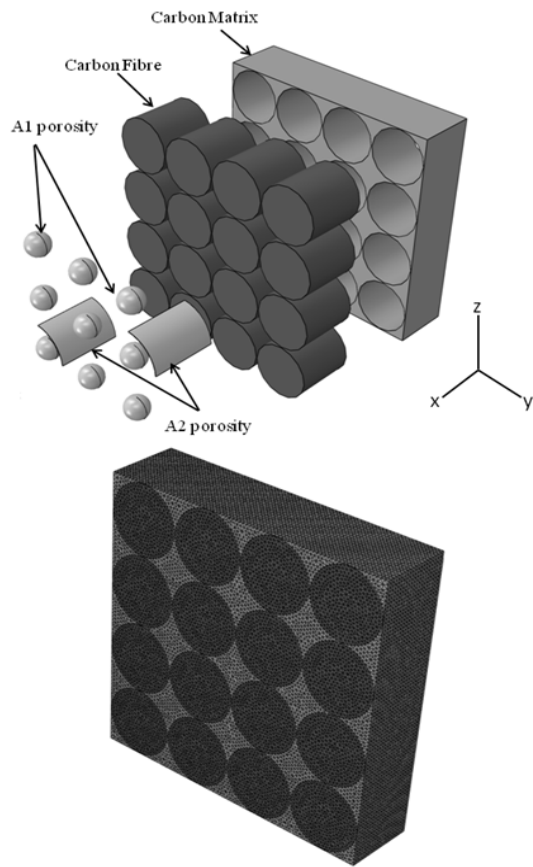


FIG. 8 MODEL A WITH ITS FE MESH

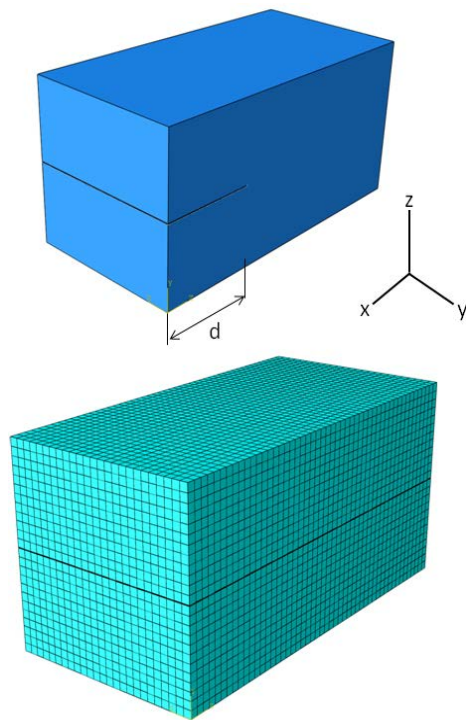


FIG. 9 MODEL B WITH ITS FE MESH

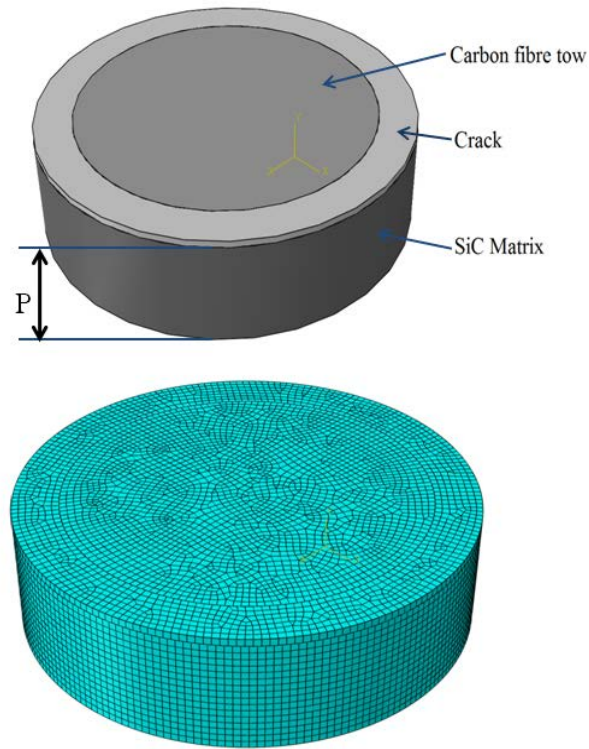


FIG. 10 MODEL C WITH ITS FE MESH

Table 5 lists the results obtained from the entire steady state thermal modelling process. Table 6 compares the thermal diffusivities obtained by FE transient analyses and experimental work.

TABLE 4 THE DEGRADATION OF THERMAL CONDUCTIVITY IN THE FIBRE TOW (W/M.K)

Thermal Conductivity	Model A		Model B	Model C
	without porosity	with porosity		
Longitudinal (//)	52.877	52.383	52.325	51.014
Transverse (⊥)	18.18	17.852	17.5	17.5

TABLE 5 THE DEGRADATION OF THERMAL CONDUCTIVITY IN THE COMPOSITE UNIT CELL (W/M.K)

Porosity	Carbon Tow		SiC Matrix		Composite Unit Cell		
	//	⊥	//	⊥	X	Y	Z
No porosity	52.877	18.18	120.7	120.7	68.46	64.75	72.32
Class A	52.383	17.852	120.7	120.7	68.18	64.45	72.08
Class A+B	52.325	17.5	120.7	120.7	67.95	64.185	71.9
Class A+B+C	51.014	17.5	51.014	120.7	58.38	55.56	61.15

Results and Discussion

Without Porosity

The transverse and longitudinal thermal conductivities for the carbon fibre tow are obtained by excluding the porosity from the analyses of model A, the results are given in the second column of Table 4. These values with the thermal conductivities of the virgin SiC matrix (120.7 W/m-K) (from Table 1) are employed in the composite unit cell to predict the thermal conductivities of the virgin composite, the results are given in the second row of Table 5.

With Class A Porosity

The degraded thermal conductivities of the carbon fibre tow are obtained from model A, whose results are given in the third column of Table 4. These values with the thermal conductivities of the virgin SiC matrix (120.7 W/m-K) (from Table 1) are used in the composite unit cell to predict the thermal conductivities of the composite, the whose results are given in the third row of Table 5. It can be seen that class A porosity caused less than 0.5% reduction in the thermal conductivities of the composite.

With Classes A and B Porosities

The reduced thermal conductivities of the carbon fibre tow are obtained from model B, whose results are given in the fourth column of Table 4. These values with the thermal conductivities of the virgin SiC matrix (120.7 w/m.k) (from Table 1) are incorporated in the composite unit cell to predict the thermal conductivities of the composite, the results are given in the fourth row of Table 5. It can be seen that class B porosity caused less than 0.5% reduction in the thermal conductivities of the composite.

With Classes A, B and C Porosities

The reduced thermal conductivities of the carbon fibre tow and the SiC matrix are obtained from model C, and the results are given in the last column of Table 4. These values are incorporated in the composite unit cell to predict the final thermal conductivities and diffusivities of the composite, the resulted thermal conductivities are given in the last row of Table 5. It can be seen clearly that class C porosity (matrix cracks) had a dominant effect on the thermal conductivity which caused around 14% reduction in the overall thermal conductivity of the composite unit cell. The measured and predicted thermal diffusivities of the composite are shown in Table 6. The predicted values

are 5-9% lower than the experimental results. Nevertheless, the finite element results obtained from this study are in good agreement with the experimental results.

TABLE 6 COMPARISON OF THE THERMAL DIFFUSIVITY (MM²/SEC) OBTAINED BY FE ANALYSIS AND EXPERIMENTAL WORK

Direction	Experimental	FE Modelling	% Difference
X direction	34.84	32.45	-6.86
Y direction	33.5	32.01	-4.45
Z direction	37.5	34.22	-8.75

Conclusion

Various steady-state and transient thermal analyses have been carried out on four different models constructed at different length scales in attempt to investigate the effect of manufacturing porosities on the degradation of thermal transport properties of a 3-D orthogonal C-SiC composite. From the output results, it was found that, inter-fibre porosity (class A) and trans-tow cracks (class B) have a negligible effect on thermal transport of the composite. The matrix cracks (class C), however, have a dominant effect on the degradation of thermal transport properties of the composite.

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